Beyond the Standard Model

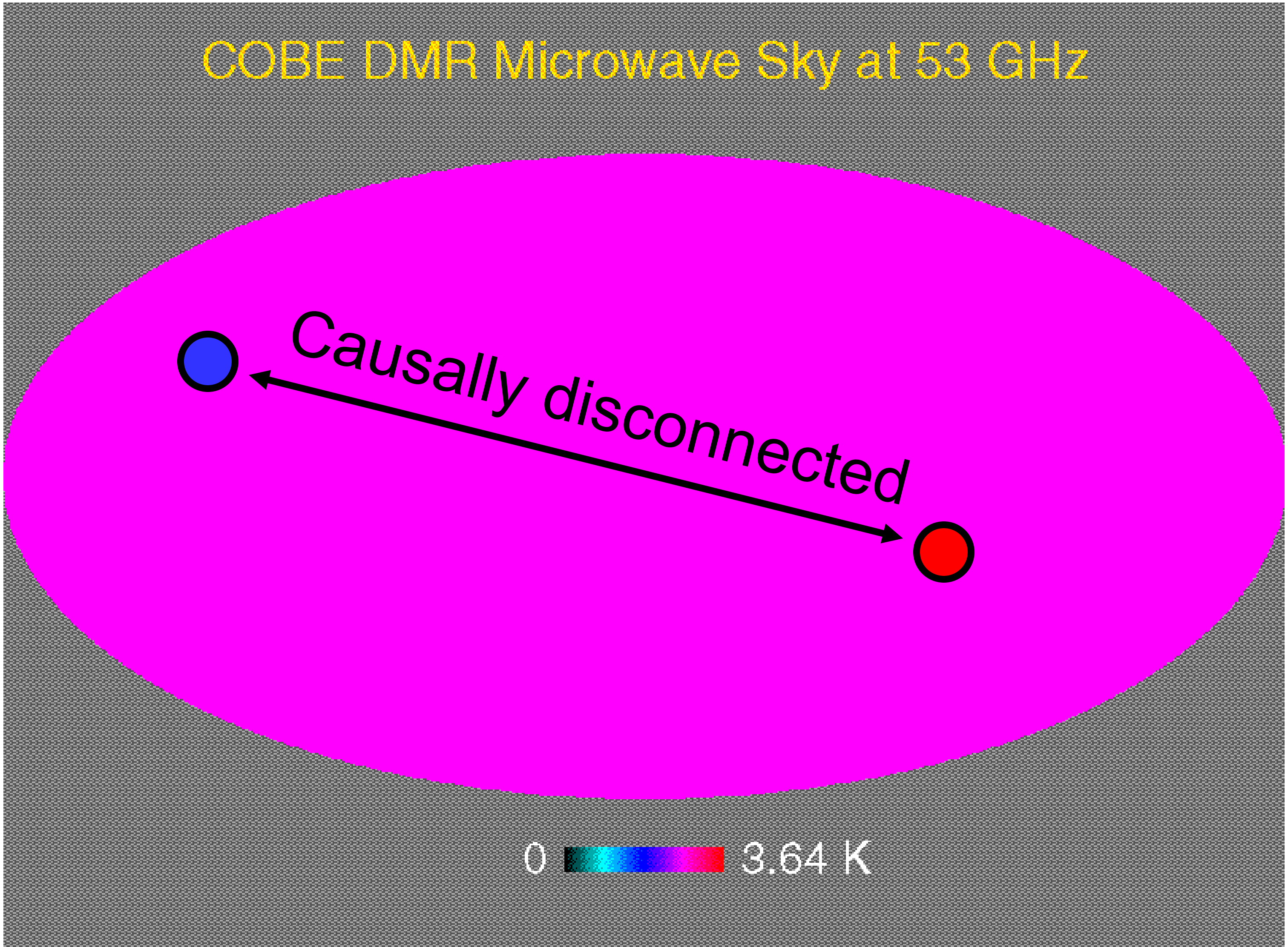
Problems with the Standard Model

- The standard cosmological model is very successful in explaining many observational facts, but it has some problems. (Who doesn't?)
  - Horizon problem
  - Flatness problem
  - Relic problem
  - Structure problem

Horizon problem

- The CMB streams to us from the surface of last scattering at z=1200. The cosmological horizon at that time looks on our sky as a region 2 degree across - 4 times larger than the Moon or the Sun. Two regions on the sky more than 2^0 apart never communicated with each other. How can they have the CMB temperature agree to one part to 100,000?
- **For its age the universe is way too large.**

Horizon problem



Flatness problem

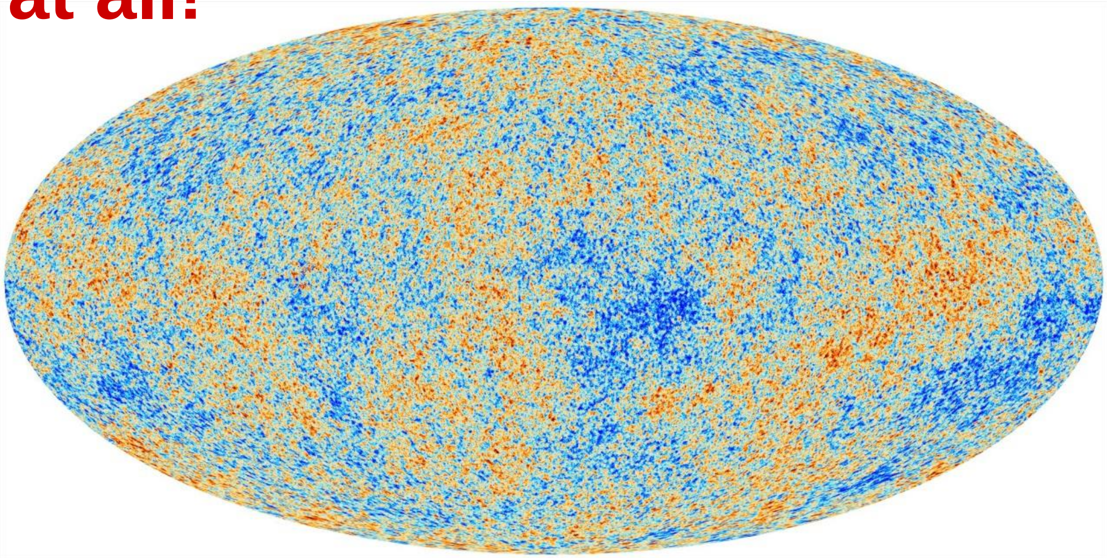
- Observations tell us that the space within our cosmic horizon is curved by not more than 1%. Hence, the universe is very close to being flat. As it expands, it moves away from being flat (becomes more and more “non-flat”). If it is close to being flat now, **it started incredibly close to being flat**.

Relic problem

- During the early stages of the evolution of the universe all kinds of elementary particles are created. Some of them may be stable. **Where are they now?**
- (That may not be a big problem after all, we do need some particles to make Dark Matter.)

Structure problem

- Why are we here? (In other words, how the fluctuations that became galaxies originated in the first place?)
- The early universe spent most of its life in thermal equilibrium. **There should be no fluctuations there at all!**



Inflation

- In 1982 two cosmologists, American Alan Guth and Russian Alexei Starobinsky independently offered a solution:

  If the universe is too large for its age, then it should have expanded a great deal in the past.

- This expansion has to be very fast, much faster than the universe is expanding today.

Inflation

- This kind of expansion is called ***inflation.*** Before inflation, our current horizon was a tiny-tiny region of the universe, much smaller than a horizon at that epoch. It had more than enough time to fully come into a thermal equilibrium.
- The region that before inflation was well within a horizon, now can be larger than a horizon. During normal expansion a horizon increases in size. This means that during inflation a horizon was ***decreasing*** in size.

”Superluminal expansion”

- Two inertial observers that were within sight of each other could later move outside each other's horizon.
- This is sometimes called ``superluminal expansion''. It of course does not mean that the Special Relativity is violated, just that the horizon is moving inward rather than outward. This can happen when the expansion of the universe accelerates.

What can cause such a fast expansion?

A. The speed of light became larger.
B. The space-time exploded at the first moment.
C. The gravity force became repulsive.
D. The universe started expanding incredibly fast.

Inflaton

- Accelerated expansion of the universe is caused by substance that has repulsive gravity.
- Such substance does exist - for example, the Dark Energy.
- The substance that drove inflation is called ***inflaton*** (this a generic name, we don’t know what inflaton actually is).
- Our current Dark Energy may be the inflaton, although no one succeeded in making a model where this is the case.

How many inflations have been there?

A. Just 1.
B. At least 2.
C. More than 4.
D. Infinitely many.

Inflationary expansion

- During inflation (about 10^{-35} seconds) the universe expanded by a factor of at least 10^{30}, or, more likely, by something like

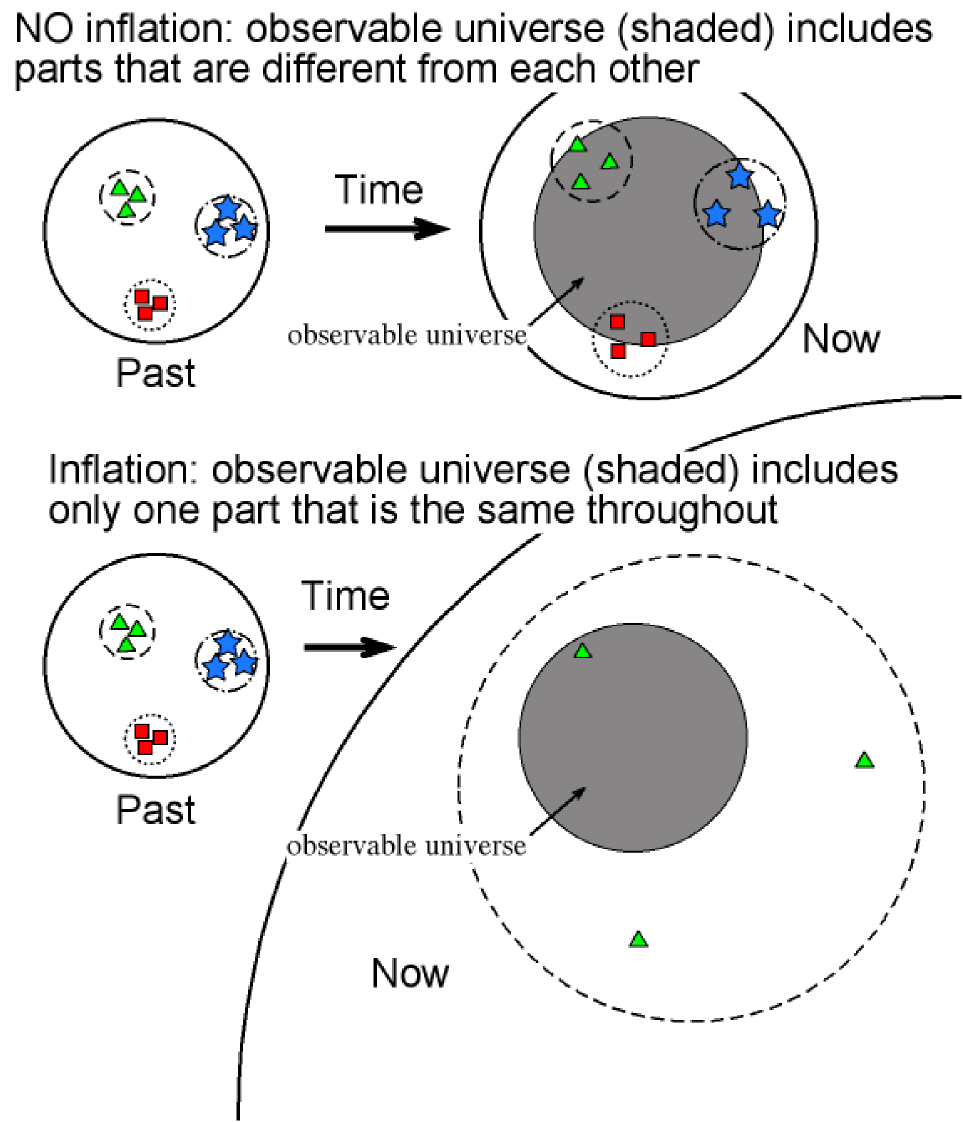
$$10^{10^{13}} = 10^{10,000,000,000,000}.$$

- This number is **totally incomprehensible**!!!

- How does inflation help with the problems of the standard model?

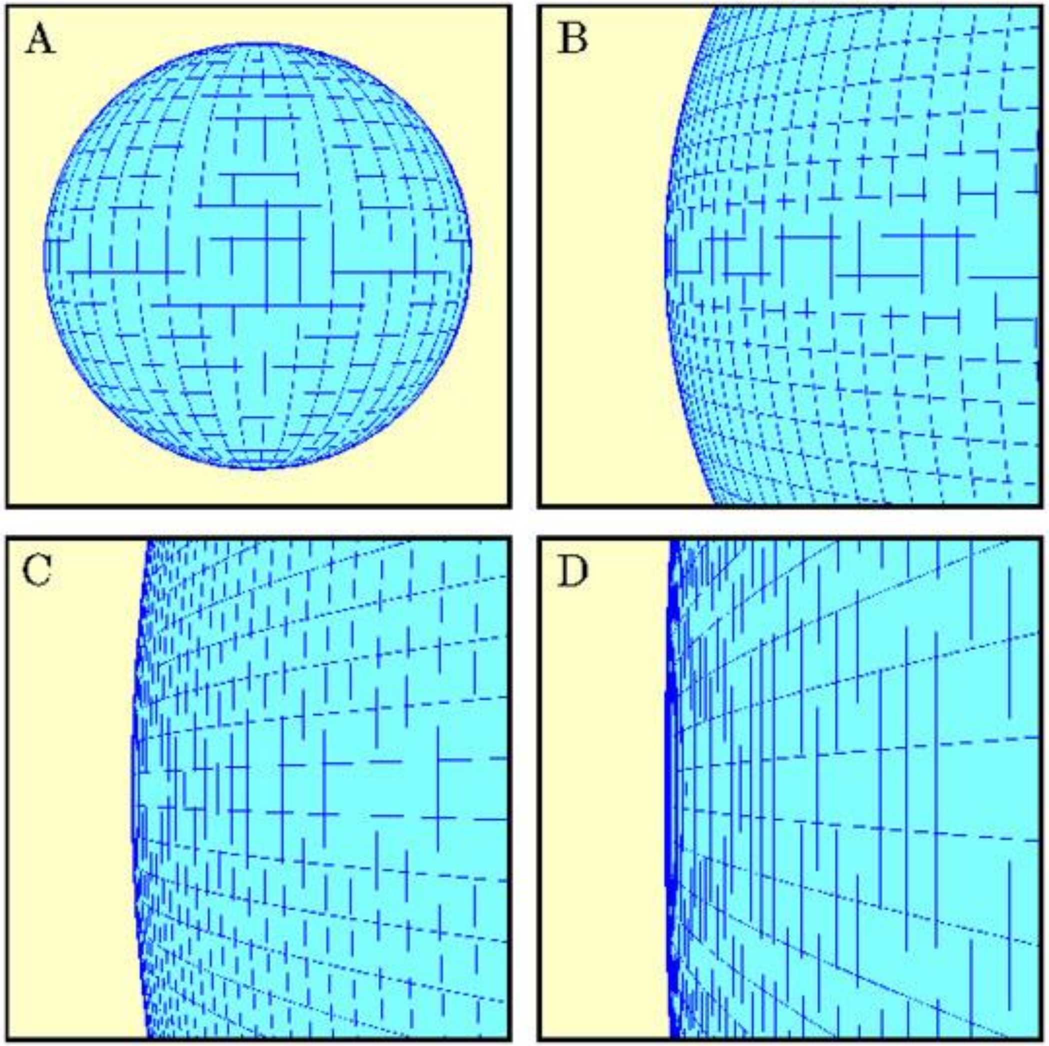
Horizon problem

- All the observable universe comes from a very small region, which was well in thermal equilibrium back then.



Flatness problem

- Since the universe inflated, it became much flatter than it was in the beginning.
- **Important prediction**: If inflation indeed took place, the universe should be flat now.



Structure problem

- In the standard model, the universe was in thermal equilibrium, thus all fluctuations should be suppressed.
- Recall: in Quantum Mechanics usual conservation laws are allowed to be violated for a very short time and on very small spatial scales (Heizenberg Uncertainty Principle):

$$\Delta p \Delta x \geq \frac{1}{2}\hbar \qquad \Delta E \Delta t \geq \frac{1}{2}\hbar$$

Structure problem

- Uncertainty Principle implies that there are always fluctuations in any conditions (albeit very very small). Those fluctuations are called ***quantum fluctuations***.
- These fluctuations can ***never*** be suppressed.
- Quantum fluctuations exist only on very tiny scales. You cannot make galaxies out of these fluctuations unless...

Structure problem

- Inflation increases the size of the universe, and the scales of all fluctuations so much that quantum fluctuations become fluctuations on the scales of galaxies, clusters of galaxies, horizon scales, and even beyond.
- Why don't these fluctuations get suppressed later, when the universe again gets into thermal equilibrium?

Structure Formation

- Fluctuations outside the horizon cannot grow or decay – they are not in causal contact with themselves.
- Inflations takes the quantum fluctuations outside the horizon, thus "protecting" them from the action of thermal equilibrium.
- After inflation the horizon increases with time. Fluctuations that were stretched outside the horizon can now move inside it and get suppressed.

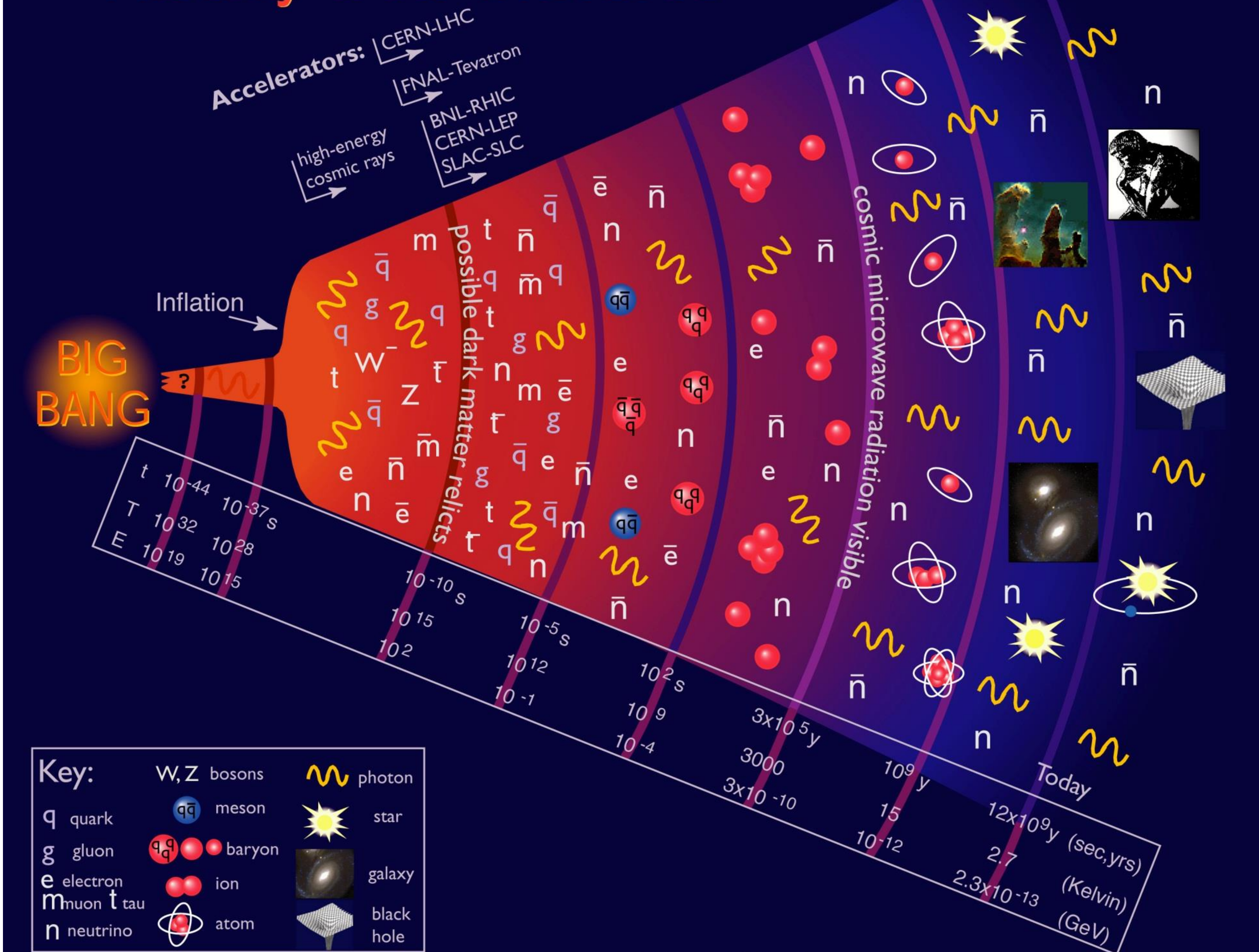
Structure Formation

- Small scale fluctuations that moved inside the horizon long time ago are indeed suppressed.
- Fluctuations on galaxy scales and larger moved inside the horizon rather recently, after recombination, and the thermal equilibrium was not maintained at that time. They did not get suppressed, they grew due to gravity.
- That is how galaxies (and everything inside them) formed.
- We all owe our lives to inflation!!!

The End of Inflation

- The inflationary expansion of the universe was driven by the repulsive gravity of the inflaton. We are not made out of inflatons, so sooner or later inflation stops.
- This is called a process of ***reheating***: inflaton must decay into normal matter (quarks, leptons, perhaps WIMPs). Normal matter then quickly comes into thermal equilibrium and the normal Big Bang history begins.

History of the Universe



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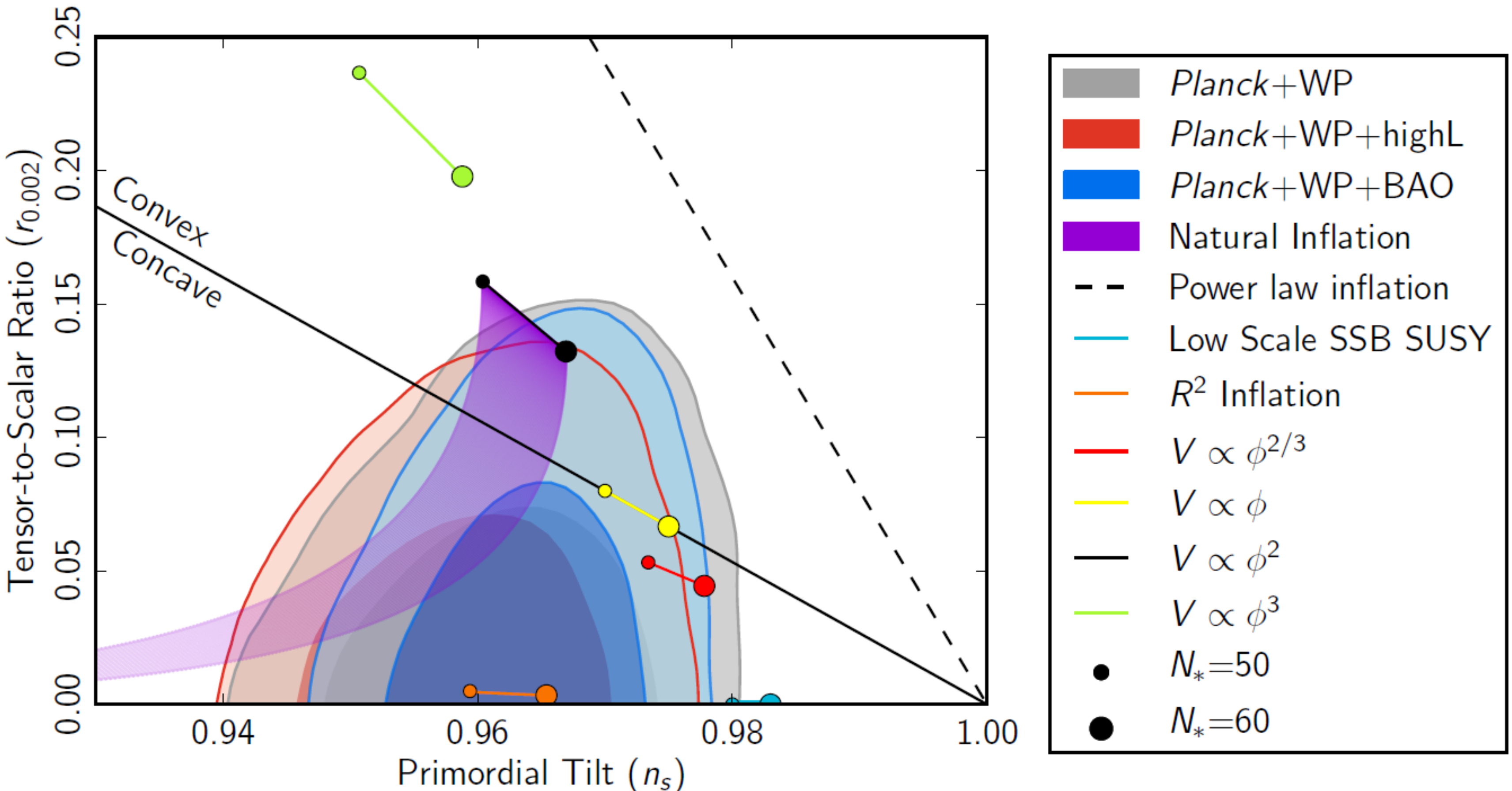
Inflation and Planck

- Planck is the first experiment that places interesting constraints on inflation.



Chaotic inflation and eternal universe

- Inflation seemed to fit very well between the GUT era and quark era, until early 1990s.

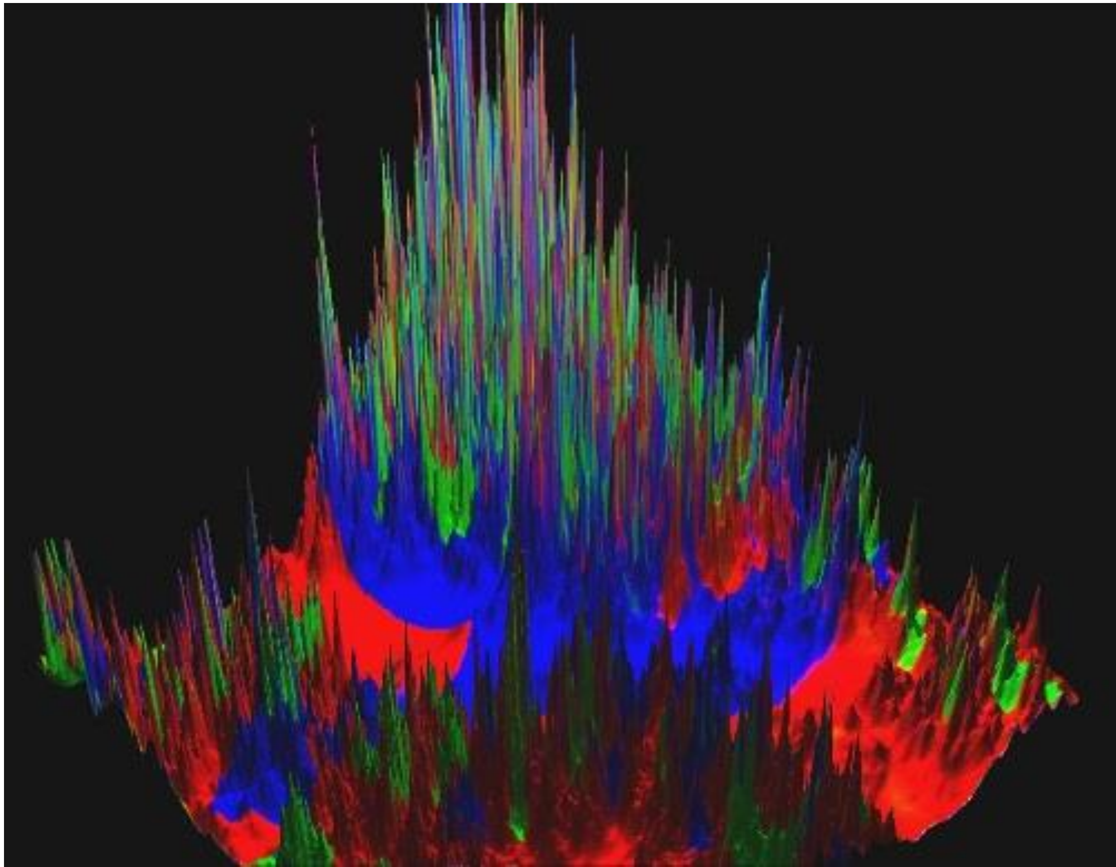
- Then Andrei Linde (used to be Russian, now professor at Stanford) realized that those quantum fluctuations that seed galaxies well after inflation, can create new “universes” (or, more precise, inflating regions) during inflation!

Chaotic inflation and eternal universe

- The universe constantly recreates its initial conditions. Regions that expanded enough during inflation will continue inflating, creating huge homogeneous and isotropic regions (which we used to call a universe before). Other regions can be thrown back to the initial conditions by quantum fluctuations, and will begin everything anew, again creating new homogeneous and isotropic regions and new initial conditions.

Chaotic inflation and eternal universe

- Such a universe will exist forever, and may have existed forever.
- The Big bang will then be only a part of the universe, and the universe as a whole exists at all times in the infinite space.



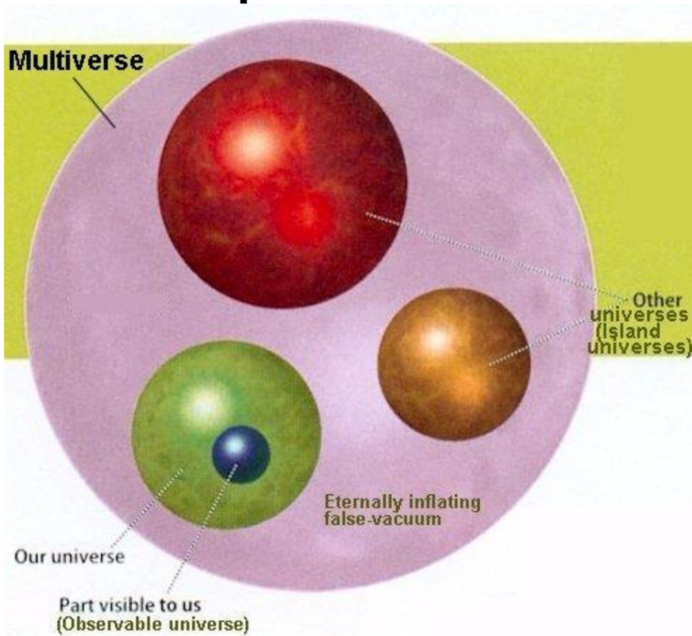
Chaotic inflation and eternal universe

- Such a universe is eternal and infinite, it is not homogeneous or isotropic on very-very-very-... large scales ($10^{10^{13}}$ light years or larger), but it contains very large regions (sub-universes) that are homogeneous and isotropic.
- Different sub-universes may have very different cosmological parameters etc. We happened to live in one that has the values we measure today. Others may have different omegas, Hubble constants, CMB temperatures, etc.

Chaotic inflation and eternal universe

- The explanation why our universe is such as it is then becomes simple: there are infinite number of different universes, and we just happened to be in this one. This is, perhaps, the weakest possible form of the anthropic principle.

- This concept sometimes called a “multiverse”.



Quantum gravity

- General Relativity explains gravity as curvature of space-time. On the other hand, Quantum Mechanics considers all interactions as being carried by special particles, bosons. In particular, gravity should be carried by graviton.
- The difficulty in unifying the GR and QM is in this difference: how a bunch of gravitons can look like the curved space-time?
- We have no full understanding of this duality, but string theory offers at least a possible explanation.

Space-time foam

- Since quantum fluctuations are present everywhere all the time, they should be present in quantum gravity as well. Since the space-time itself is a part of quantum gravity, there should be quantum fluctuations in space-time on Planck scales: 10^{-33} cm and 10^{-43} seconds.
- On this tiny spatial and time scales the space-time is not smooth, but fluctuates. This is often called the space-time foam. We have no clear picture what it actually means.

The birth of the universe

- We really do not know how the universe was born. Perhaps, it exists forever with chaotic inflation. Perhaps, it was born at one “moment” from the space-time foam, when one of the quantum fluctuations became quite large by chance, and started expanding.
- In both these cases the universe is infinitely larger than what we can see around us, and has infinitely many homogeneous and isotropic regions which we identified with the whole universe during most of this class.

The Class Is Over

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